Differential Load Driver Circuits

This application claims priority to co-pending Chinese Application Serial No. 03123949.8 filed May 29, 2003, the teachings of which are hereby incorporated by reference in its entirety.

1. Field of the Invention

The present invention relates to a differential load driver circuit, and more particularly, a differential load driver circuit that operates in both a linear mode for low current requirements and a PWM mode for high current requirements.

2. Background of the Invention

PWM (Pulse Width Modulation) techniques are frequently used in power electronics to drive large load currents because of its high efficiency. In comparison, linear current are almost never used in driving large load currents because of its poor efficiency. However, because there are no switching signals in a linear current source, the output current will not have any ripple. A PWM driven load current will inevitably experience some ripple, the amplitude dependent on the cutoff frequency and attenuation of the filtering network.

4 power MOFSETs (Metal Oxide Semiconductor Field Effect Transistor) connected in an H-bridge is commonly used to drive a differential load. Figures 1 and 2 depict conventional H-Bridge circuits used to drive a load. The H-Bridge circuit depicted in the figures includes four switches (12. 14, 16 and 18) arranged as shown to drive a load 19, as is well understood in the art.

Figure 1 depicts current flowing from left to right, and shall be defined herein as "cooling". Figure 2 depicts current flowing from right to left and shall be defined herein as "heating". Figures 1 and 2 shows the signals required to drive 4 H-bridge connected power MOSFET to

drive a resistive load in the heating and cooling mode. For example, to drive the load in the cooling mode (Figure 1), PWM signals are applied to P1 and N1. Whereas P2 is disable and N1 is fully turned on. This operation is similar to a buck converter, as is known in the art. The duty cycle of the PWM signal will control the current flowing the resistive load. Filter elements L1, C1, L2 and C2 will attenuate the ripple current through the load. Each switch has an associated pre-driver circuit (not shown) that drives the switch at an appropriate level.

Such a design will experience some problems when small current is required through the load. At small load current, the duty cycle of the PWM signals are correspondingly reduced. However, the driving capability of pre-drivers circuits is limited in terms of duty cycle. Moreover, the gate capacitances of the power MOFSETs are quite significant. Hence, it is not possible to drive the power MOFSETs at very small duty cycle resulting in the system not being able to output small load current in either the heating or cooling mode. Likewise, the percentage of ripple current will increase significantly as the average DC value of the load current decreases.

Figures 3 and 4 show another variation of Figures 1 and 2 in which one set of the filter elements, L2 and C2, are removed. This generally results in costs savings and a smaller form factor. However, the circuit of Figures 3 and 4 still suffers from the same deficiencies of the circuit of Figure 1 and 2, i.e., increased ripple at low current conditions.

SUMMARY OF THE INVENTION

In one aspect, the present invention provides an H-Bridge load driving circuit, comprising four power switches forming an H-Bridge circuit selectively coupled to a load to supply current to said load; and at least one current source; wherein said circuit being adapted to couple said power switches or said current source to said load as a function of load current.

In another aspect, the present invention provides a differential load driving circuit comprising: a plurality of power switches selectively coupled to a load to supply current to said load; a plurality of power switch driving circuits operable to control the conduction state of said power switches and to selectively couple at least one of said plurality of power switches to a PWM signal; and at least one current source. The current source is coupled to said load to deliver current to said load during low current conditions at said load, and said PWM signal coupled to said load to deliver current to said load during high current conditions at said load.

In another aspect, the present invention provides an H-Bridge load driving circuit, comprising four power switches forming an H-Bridge circuit selectively coupled to a load to supply current to said load; a plurality of power switch driving circuits operable to control the conduction state of said power switches and to selectively couple at least two of said plurality of power switches to a PWM signal; and at least one current source. The H-Bridge circuit having a first mode in which said current source is coupled to said load to supply current to said load and a second mode in which at least two of said power switches are coupled to said PWM signal to supply current to said load.

In yet another aspect, the present invention provides a differential driving circuit for driving a thermal electric cooler, said circuit comprising: a plurality of power switches selectively coupled to a thermal electric cooler load to supply current to said load; a plurality of power switch driving circuits operable to control the conduction state of said power switches and to selectively couple at least one of said plurality of power switches to a PWM signal; and at least one current source. The differential driving circuit having a first mode in which said current source is coupled to said load to supply current to said load and a second mode in which

at least two of said power switches are coupled to said PWM signal to supply current to said load.

It will be appreciated by those skilled in the art that although the following Detailed Description will proceed with reference being made to preferred embodiments and methods of use, the present invention is not intended to be limited to these preferred embodiments and methods of use. Rather, the present invention is of broad scope and is intended to be limited as only set forth in the accompanying claims.

Other features and advantages of the present invention will become apparent as the following Detailed Description proceeds, and upon reference to the Drawings, wherein like numerals depict like parts, and wherein:

Brief Description of the Drawings

Figure 1 is a conventional H-Bridge load driving circuit depicted in cooling mode of operation;

Figure 2 is a conventional H-Bridge load driving circuit depicted in heating mode of operation;

Figure 3 is another conventional H-Bridge load driving circuit depicted in cooling mode of operation;

Figure 4 is another conventional H-Bridge load driving circuit depicted in heating mode of operation;

Figure 5 is one exemplary circuit diagram of an H-Bridge load driver circuit operating in a linear cooling mode according to a first embodiment of the present invention;

Figure 6 is another exemplary circuit diagram of an H-Bridge load driver circuit operating in a PWM cooling mode according to a first embodiment of the present invention;

Figure 7 is another exemplary circuit diagram of an H-Bridge load driver circuit operating in a linear heating mode according to a first embodiment of the present invention;

Figure 8 is another exemplary circuit diagram of an H-Bridge load driver circuit operating in a PWM heating mode according to a first embodiment of the present invention;

Figure 9 depicts an exemplary graph showing the relationship between linear current mode and PWM mode of the present invention;

Figure 10 is one exemplary circuit diagram of an H-Bridge load driver operating in a PWM heating mode according to a second embodiment of the present invention;

Figure 11 is one exemplary circuit diagram of an H-Bridge load driver circuit operating in a linear cooling mode according to a third embodiment of the present invention;

Figure 12 is another exemplary circuit diagram of an H-Bridge load driver circuit operating in a PWM cooling mode according to a third embodiment of the present invention;

Figure 13 is another exemplary circuit diagram of an H-Bridge load driver circuit operating in a linear heating mode according to a third embodiment of the present invention;

Figure 14 is another exemplary circuit diagram of an H-Bridge load driver circuit operating in a PWM heating mode according to a third embodiment of the present invention; and

Figure 15 is an exemplary controller for controlling the operation of a load driver circuit according to the present invention.

Detailed Description of the Exemplary Embodiments

In the following Detailed Description, the load 19 may include a Thermal Electrical Cooler (TEC). Such a device is operable in heating and cooling modes, depending on direction of current flow. A TEC is used as a heating/cooling component to control precise temperature of devices, especially in Optical communication devices. When positive current passes through

TEC, TEC will heat device with precise temperature requirement, when negative current passes through TEC, it will cool the device. However, the present invention is not intended to be limited by such a load or to any type of load

The following Detailed Description shall proceed with a focus on the power train of the differential load driver. Conventional protection features associated with such applications such as over temperature and over current circuits will not be discussed, but may be included and are deemed within the spirit and scope of the present invention.

The present invention is directed to a differential load driver circuit (e.g., H-Bridge circuit) that operates in both linear mode and PWM mode. Linear mode operation is selected to reduce ripple current associated with low current operation of a differential load driver. The switchover point between linear and PWM operation may be programmable and/or user definable. The switchover point may be selected, based on, for example, the desired/tolerated ripple current at the load, the capacitance of the switches in the H-Bridge circuit, and/or other considerations. In other words, the differential load driving circuit of the present invention is operable between a linear current mode and a PWM current mode as a function of load current. Therefore, the term "low" associated with low current is to be construed broadly and may include any current delivered to a load. Likewise, the term "high" associated with high current conditions is relative to low current (but higher than low current) and should be construed as any current delivered to the load above the predefined low current delivered to the load.

Additionally, the following Detailed Description will proceed with describing various embodiments of an H-Bridge differential load driving circuit. The operation of an H-Bridge circuit is very well known in the art, and such discussion shall be omitted here.

I. First Embodiment

Figures 5-8 depict a differential load driver circuit 50 according to a first exemplary embodiment of the present invention. In this exemplary embodiment, switch driving circuits 52, 54, 56 and 58 (associated with each switch P1, P2, N1 and N2, respectively) are provided to control the operation of the power MOSFET switches. Current sources 60 and 62 are provided on each side of the H-Bridge to deliver linear current to the load.

Switch driving circuits 52, 54, 56 and 58 each include a plurality of switches (as shown). The plurality of switches are selectively operated to couple the power MOSFET switch to the PWM signal or the power supply (VCC), or the PWM signal, the power supply VCC or ground. Switches 64 and 66 are operated to couple current source 60 or 62, respectively to the load. In this exemplary embodiment, the switch driving circuits include three switches to couple the power MOSFET to the PWM signal, VCC and/or ground.

The switches included in the switch driving circuits 52, 54, 56 and 58 are exemplary and as for the case of 52 and 54 only one coupling to VCC is required. The p-type switches P1 and P2 are coupled to VCC during linear mode operation and the n-type devices (N1 and N2) are coupled to VCC and ground in an alternating fashion for both heating and cooling.

Figure 5 is one exemplary circuit diagram of the H-Bridge load driver circuit 50 operating in a linear cooling mode according to a first embodiment of the present invention. In this exemplary embodiment, during low current conditions required by the load 19 current source 60 is coupled to the load through switch 64. Current source 60 is generally defined as a linear current source and may include PMOS or NMOS devices in which the output current can be controlled through a voltage or current feedback (not shown, but such feedback control is well understood in the art). Power switches P1, P2 and N2 are rendered inoperable by switch driving circuits 52, 54 and 58. Since there are no switching signals when operating in this mode, the

present invention therefore reduces and/or eliminates ripple current to the load. Also the current source can drive all the way to zero load current. Figure 7 depicts the circuit 50 in linear heating mode in which current source 62 is coupled to the load 19 via switch 66.

However, the current source will not be able to drive very large load current as power dissipation and efficiency will then become an issue. When large load current is required, the invention switches to PWM mode operation, as shown in Figure 6 (cooling) and Figure 8 (heating).

During the transition from linear to PWM and vice versa, the magnitude of the output current of the linear current sources 60, 62 must be comparable to the resultant current drive by the onset of the PWM mode of operation. It may be desirable (but not required) to reduce the difference in current discontinuity between PWM and linear mode. Such a requirement may help avoid potential oscillatory problems to the current source or the overall feedback system. Figure 9 depicts a graph 90 showing the linear mode region I and PWM mode region II. The crossover point 68 is also depicted. As depicted in the figure, it may be desirable (but not required) to ensure that the PWM mode onset current is deliberately set slightly less than the linear mode current at the switch over point. This is to ensure all load current is covered by the current control. Current control can be a voltage or current feedback information from the load.

II. Second Embodiment

In applications where only small heating current is required, the embodiment of Figure 5-8 can be modified to reduce the number of reactive components by removing and LC set as depicted in the circuit 100 of Figure 10. Figure 10 is one exemplary circuit diagram of an H-Bridge load driver operating in a PWM heating mode according to a second embodiment of the present invention. Operation of the circuit 100 in low current linear heating mode is similar to

the description above of Figures 5-8, and includes coupling current source 106 (via switch 108) to the load 19. In this embodiment, the switch driving circuits 102 and 104 are similar to switch driving circuits 52 and 56 of Figures 5-8. Switch P2 includes switch driving circuit 110. The current source in this case would be the external power PMOS P2 biased by the output of an OTA (output transconductance amplifier). A similar circuit can be constructed along these principles for small cooling current applications.

Switch driving circuit 110 is used as a bias circuit for PMOS element P2, and may include an opamp 112 and current or voltage feedback signals 114. The opamp is configured as a difference amplifier where the feedback signal is compared to a reference voltage to generate a bias signal to control the conduction state of P2 so that P2 operates as a current source. Of course, those skilled in the art will recognize that numerous current sources can be constructed and all deemed equivalent in the present invention.

III. Third Embodiment

In this embodiment of Figures 11-14, an LC filter set is eliminated. Unlike the previous embodiment, however, this embodiment is capable of delivering larger heating and cooling current. Figure 11 is one exemplary circuit diagram of an H-Bridge load driver circuit 200 operating in a linear cooling mode according to a third embodiment of the present invention. In this embodiment 2 current sources are used 210 and 212. Current source 210 is a source and current source 212 operates to sink current. When operating in the linear, cooling mode as shown in Figure 11, 210 is coupled to the load (via switch 214), N2 has is fully turned on and P2 is fully turned off. P1 and N1 are disabled. Switching circuits 202, 204, 206 and 208 couple the power MOSFETs to the appropriate source as shown in Figures 11-14 (i.e., to the PWM signal, VCC or ground).

When operating in the linear heating mode as depicted in Figure 13, source 212 is coupled to the load, P2 is fully turned on and N2 is fully turned off. P1 and N1 are disabled.

Figures 12 and 14 depict the circuit 200 operating in PWM cooling mode and heating mode, respectively. In these states the current sources 210 and 212 are decoupled from the load 19 and P1 and N1 are driven by the PWM signal (via switch driver circuits 202 and 204). P2 and N2 alternate between VCC and ground.

Of course, those skilled in the art will recognize that in the embodiments described herein a controller, as depicted in Figure 15 may be implemented to control the conduction states of the switch driving circuits and current source switches depict. The output of the controller 300 may include complementary PWM signals PWM P and PWN N for driving the PMOS and NMOS devices of the differential load driving circuit. The controller may also output switch control signals 302-308 to control the operation of the switches in the switch driving circuits (e.g., 52, 54, 56 and 58 of Figures 5-8). The controller 300 may also generate switch control signals 312 and 314 to control the switches associated with the current sources (e.g., switches 64 and 66 associated with current sources 60 and 62 of Figures 5-8). The controller may use voltage and/or current feedback information as is well known in the art to control the power delivered to the load in both linear and PWM operation. Of course, certain embodiments described herein may not need all of the signals generated by the controller, and thus, the controller can be modified to generate appropriate signals. A low current detector circuit 310 may be included to control the switchover point between linear current mode and PWM current mode. Such a detector may further include a user definable input threshold which sets the threshold between low current and PWM mode. Of course, the detector circuit 310 may be omitted in place of a predefined input into the controller, where the predefined input represents the crossover supply current (as may be

defined by a user). The controller can be a formed of custom and/or off the shelf components. Such PWM controllers are well understood in the art.

There will be numerous modifications that will become apparent to those skilled in the art. For example, although the present invention implements the differential load driver circuits with power MOSFET devices, other power switches known in the art can be used, for example BJT devices and/or other switch mechanisms. All such modifications or additions are deemed within the spirit and scope of the present invention, only as limited by the claims.